Spectroscopic Surveys: Current Status and Technical Challenges

Kyle Dawson

University of Utah

October 5, 2015

Outline

- Cosmology from Spectra
  - Baryon acoustic oscillations (BAO)
  - Redshift Space Distortions (RSD)
  - Neutrino Masses

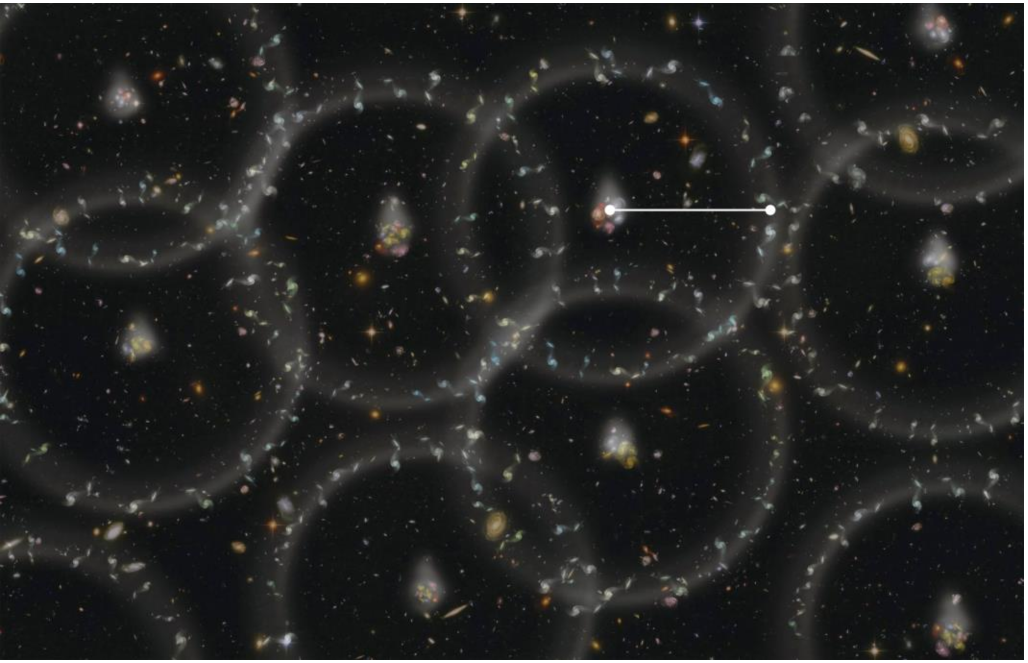
- Baryon Oscillation Spectroscopic Survey (BOSS: 2009 – 2014)
  - Establish BAO measurements with galaxies and lyman-alpha forest QSO
  - Develop measurements of redshift space distortions (RSD) with galaxies

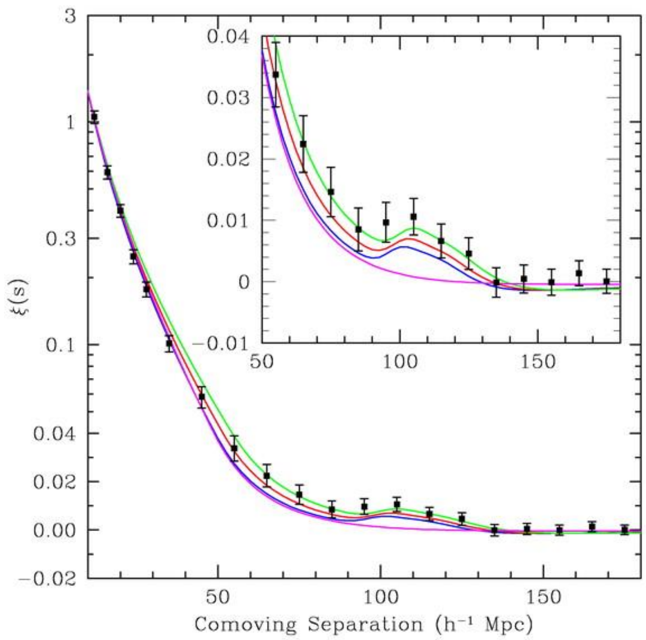
- extended Baryon Oscillation Spectroscopic Survey (eBOSS: 2014 – 2020)
  - Refine BAO technique on luminous galaxies and lyman-alpha forest QSO
  - Establish BAO technique on emission line galaxies and quasars
  - Refine RSD techniques with galaxies
  - Establish RSD measurements with QSO

- Challenges
  - Target selection and systematics
  - Spectroscopic completeness
  - Scalability

Cosmology with Spectroscopic Surveys

- Galaxies trace the matter density field and the velocity field
- Spectroscopy allows tests of expansion history
- Baryon acoustic oscillations (BAO) → expansion history
- BAO has characteristic scale of ~100 h^{-1} Mpc (comoving)

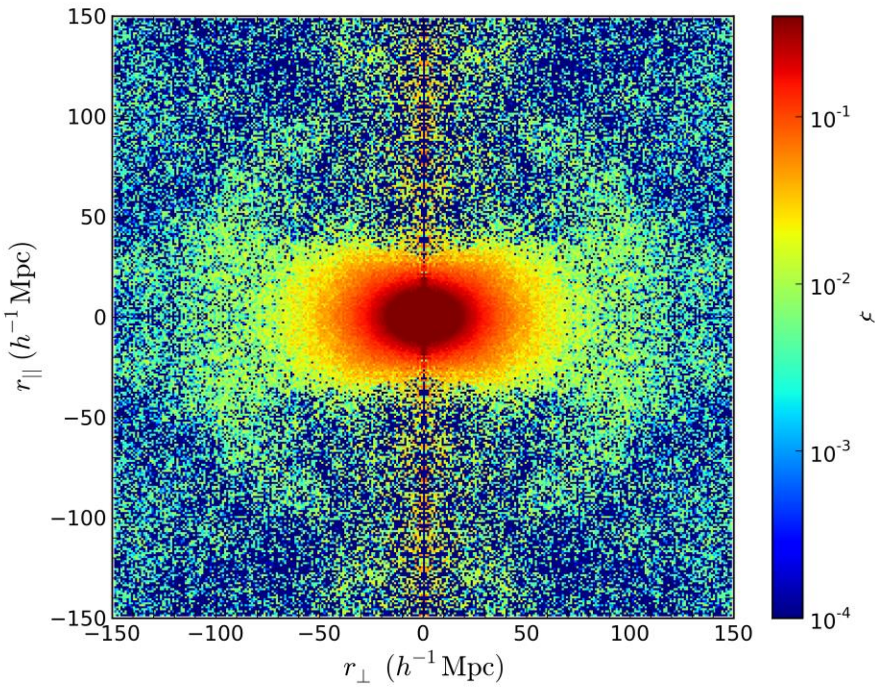


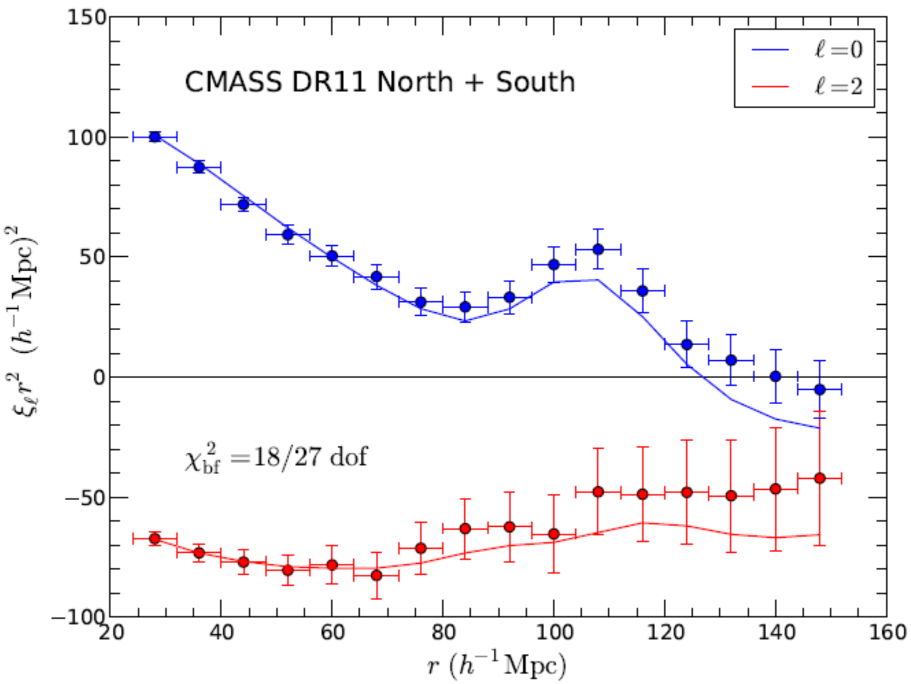


0.72 Gpc^3, 46,748 luminous red galaxies over 3816 sq degrees (Eisenstein et al, 2005)

Cosmology with Spectroscopic Surveys

- Galaxies trace the matter density field and the velocity field
- Spectroscopy allows tests of growth of structure
- Redshift Space Distortions (RSD) → growth
- Characteristic feature embedded in velocity field

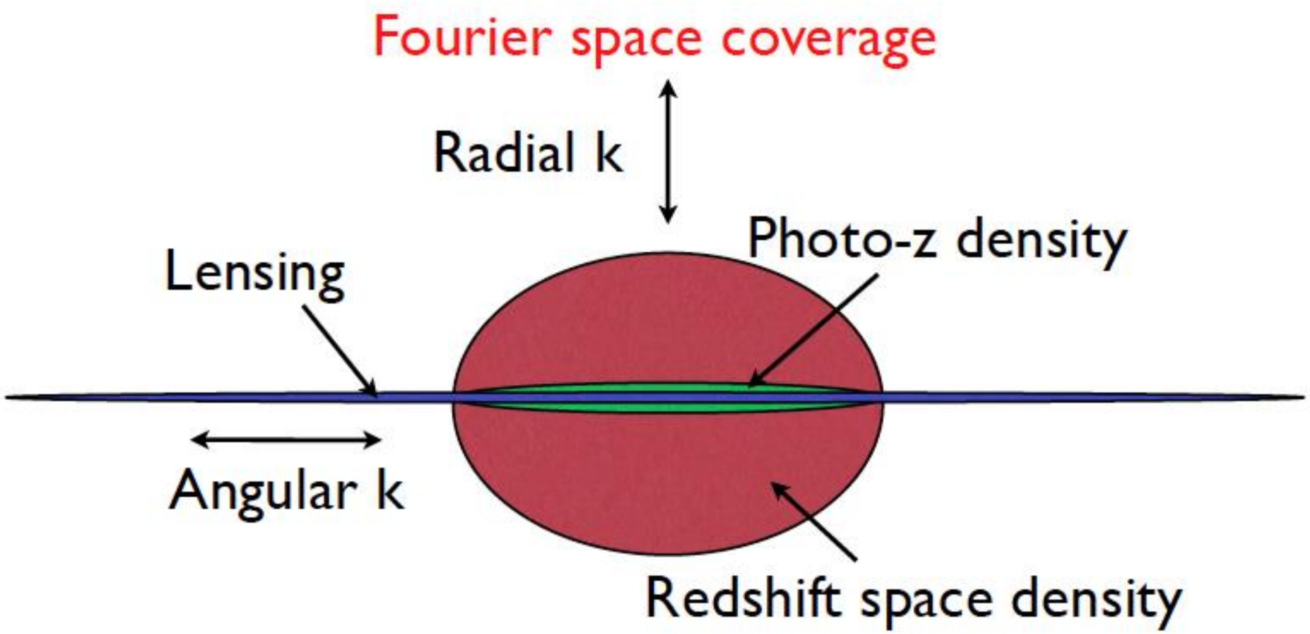




monopole and quadrupole of 690,826 BOSS galaxies at 0.43<z<0.7 (Samushia et al, 2014)

Cosmology with Spectroscopic Surveys

- Galaxies trace the matter density field and the velocity field
- Spectroscopy allows constraints on shape of matter power spectrum
- Sensitive to neutrino masses → suppression of power at small scales
- Sensitive to inflation → overall shape and higher order statistics



Red: Fourier space coverage of spectroscopic surveys
Blue: Lensing (Primarily CMB)
Green: Photo-z density field

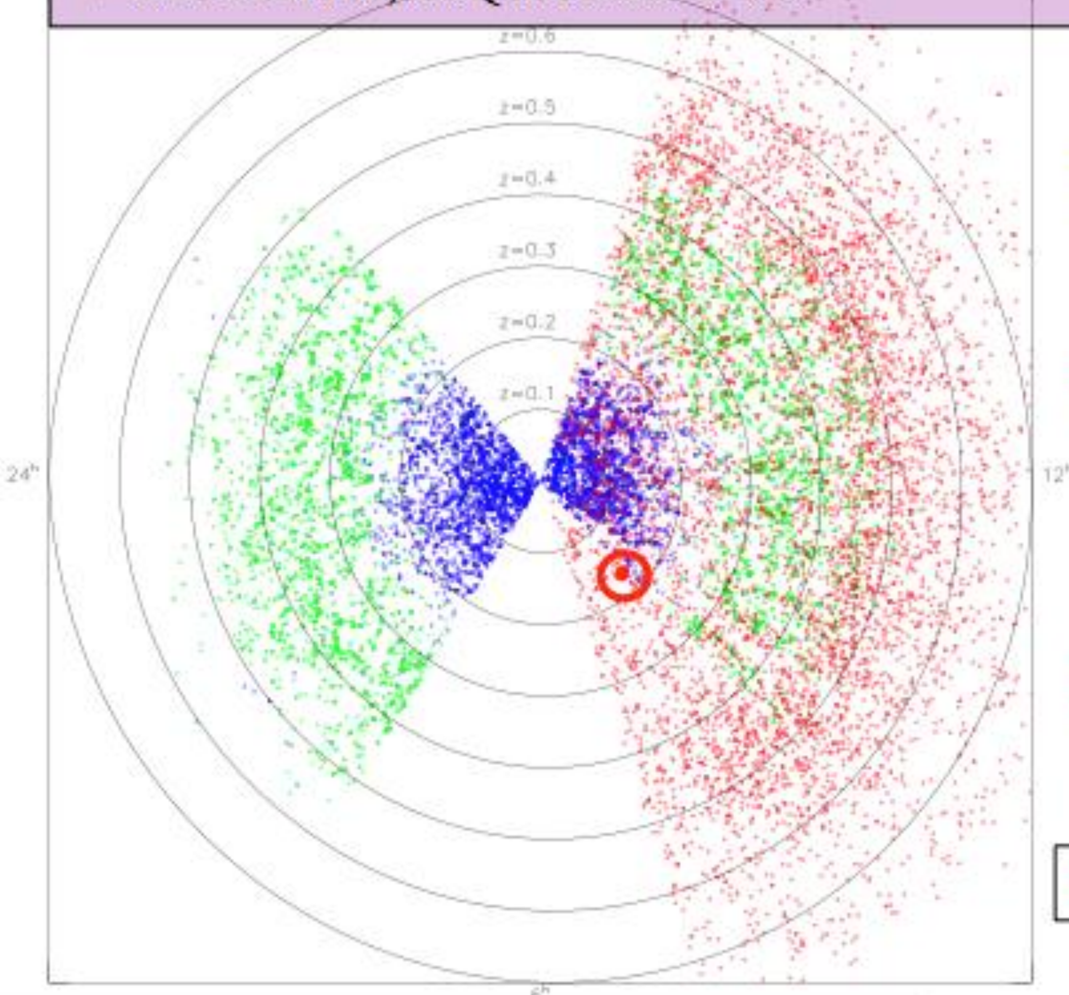
The Baryon Oscillation Spectroscopic Survey of SDSS-III

Dawson, et al., 2013

Two simultaneous spectroscopic surveys from 2009-2014

→ BAO from 1.3 million galaxies at z=0.3, 0.6

→ BAO from 160,000 QSOs at 2.2<z<3.5



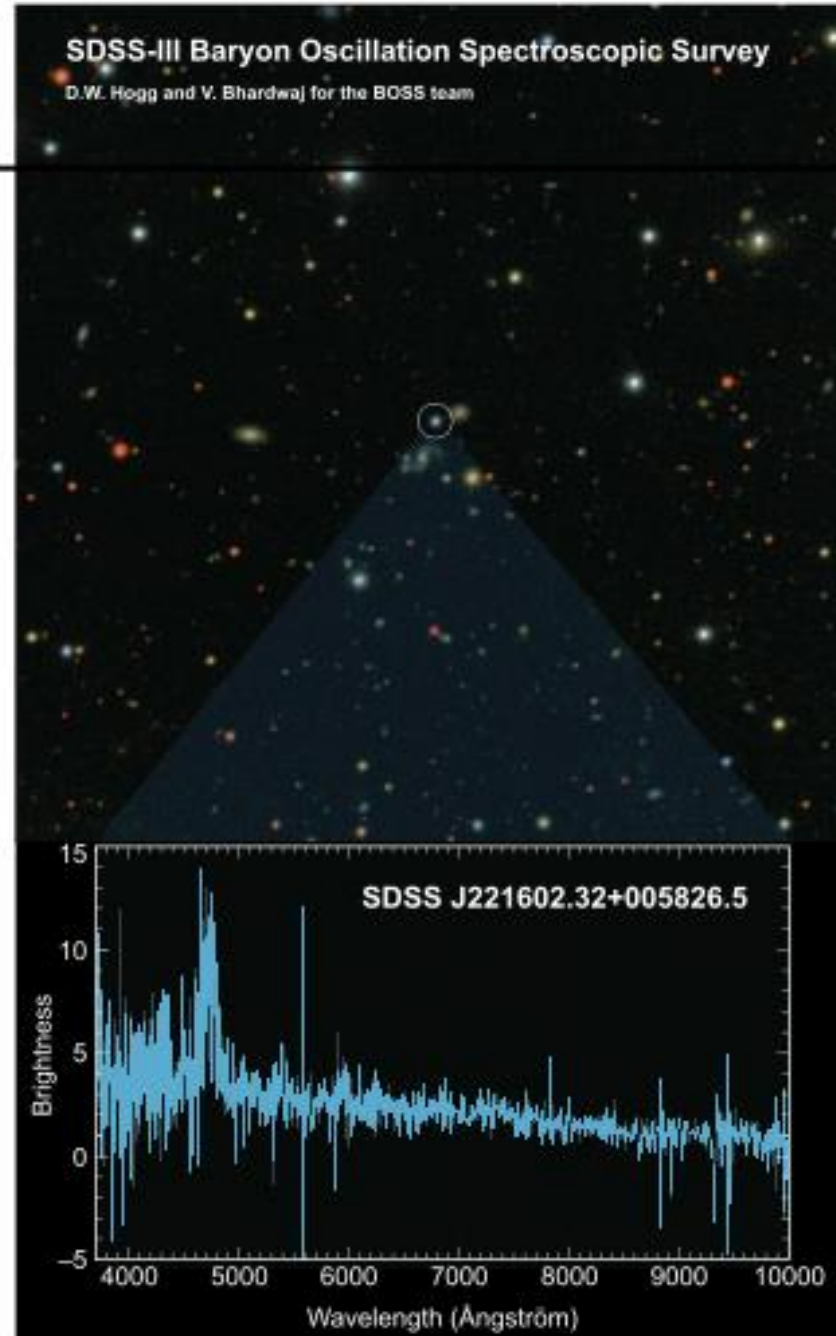
SDSS main galaxy survey
- ~1 million galaxies
- Too little volume for BAO

SDSS luminous red galaxies (LRGs)
- Sparse sampled at 10^{-4} galaxies/Mpc^3
- 47,000 galaxies by 2004
- 80,000 galaxies by 2008
- 8000 deg^2 (finish in 2008)

BOSS red galaxies
- 10,000 deg^2
- 5x sample density (shot noise)
- 2x volume

Turn this photo-z sample → spectro-z

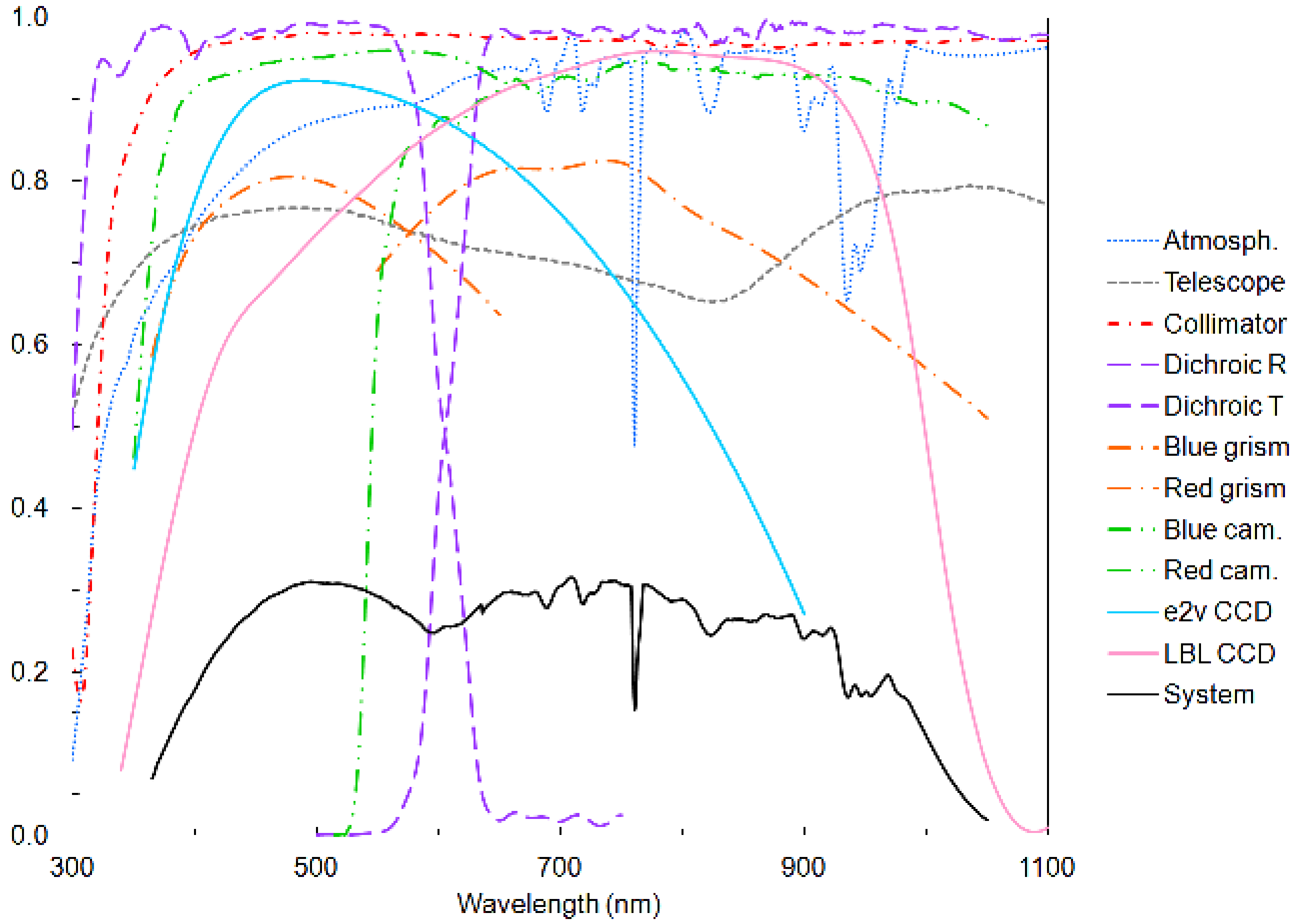
BOSS First Light 14-15 Sep 2009



BOSS Spectrographs

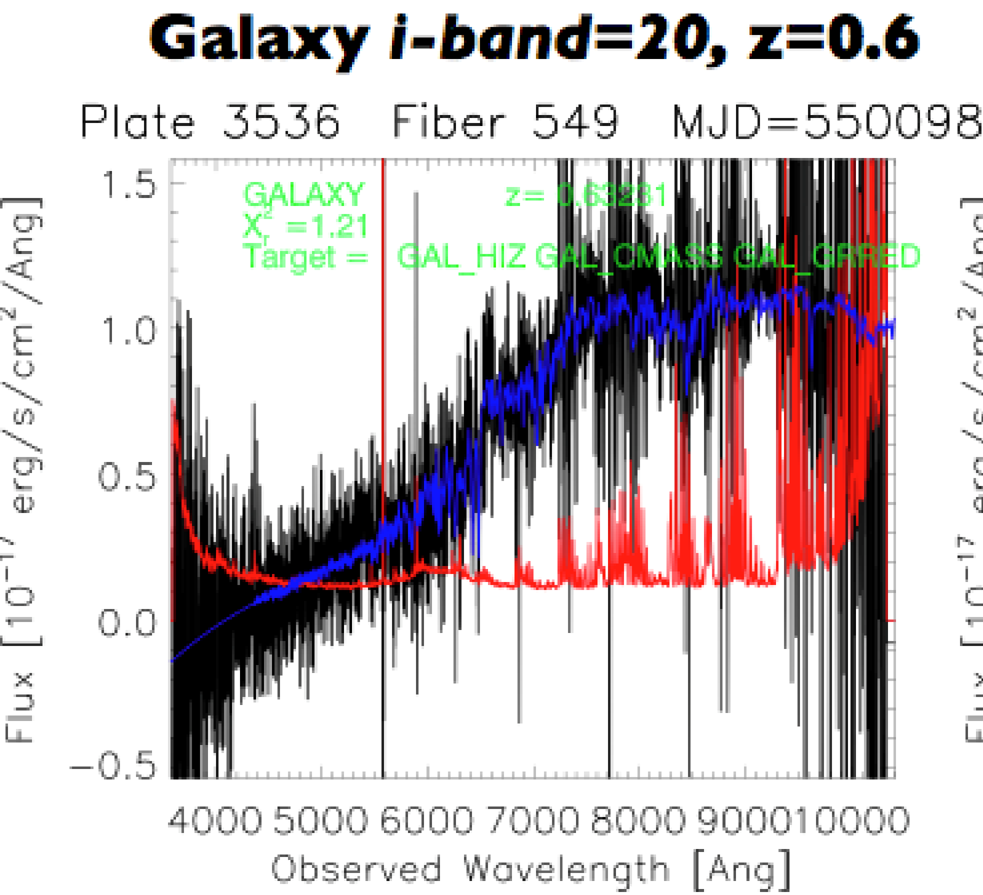
Smee et al., 2013

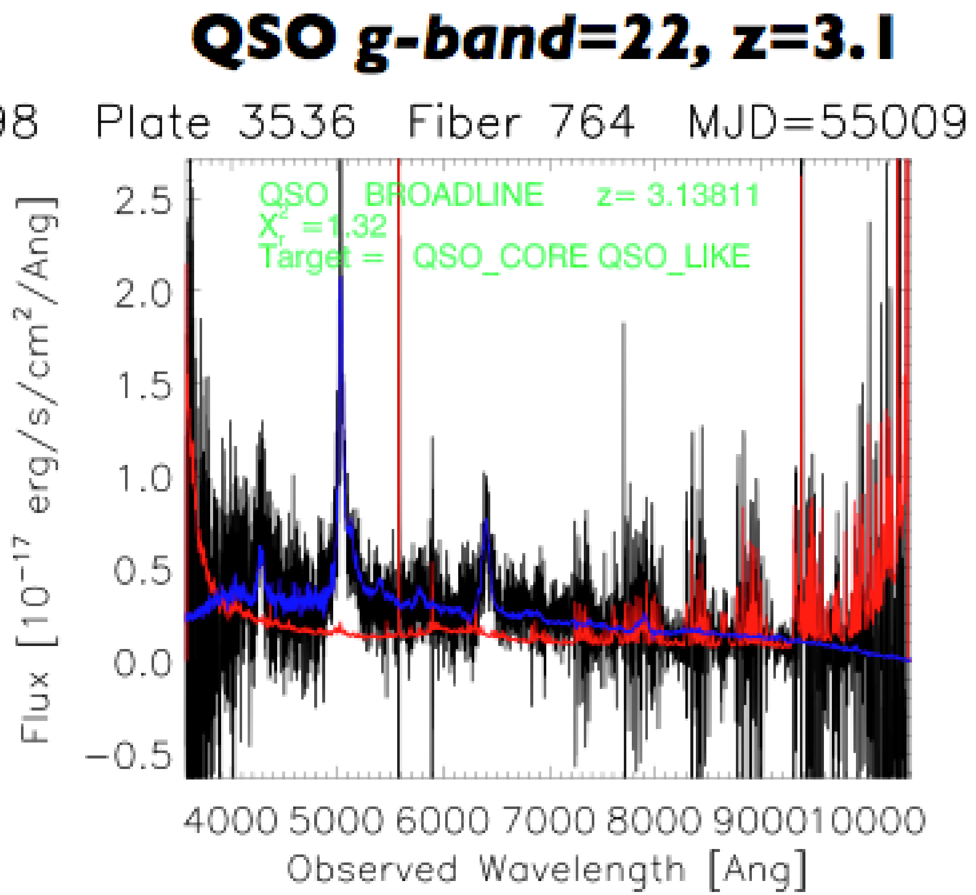
- Two 4k x 4k CCDs
- e2v CCD for optimized throughput at short wavelengths
- LBNL CCD for optimized throughput at long wavelengths



Characteristic Spectra from BOSS

- Galaxies classified automatically at 98.5% completeness
- Quasars classified via visual inspection, >400,000 spectra inspected

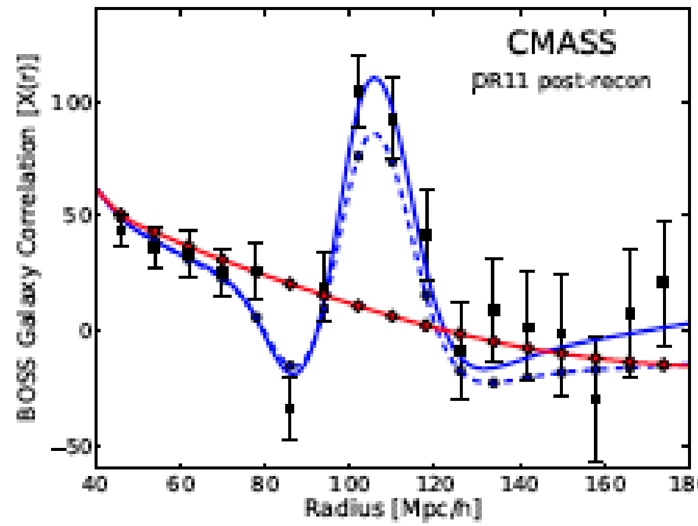


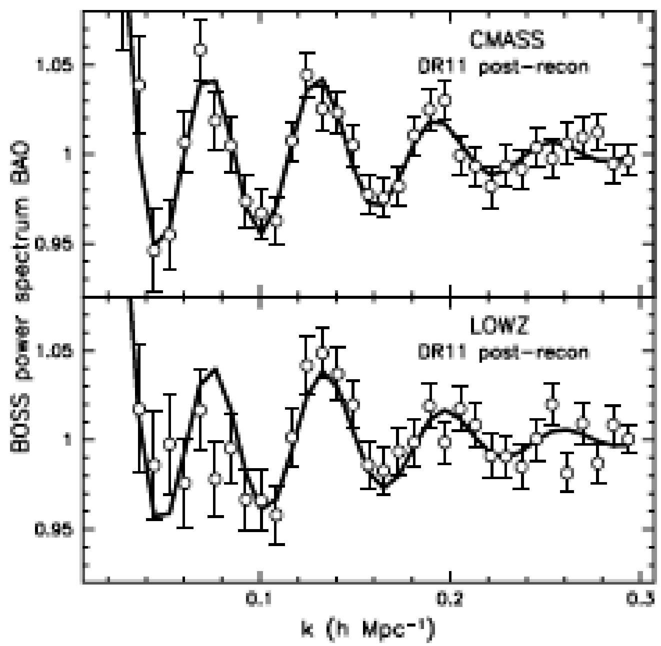


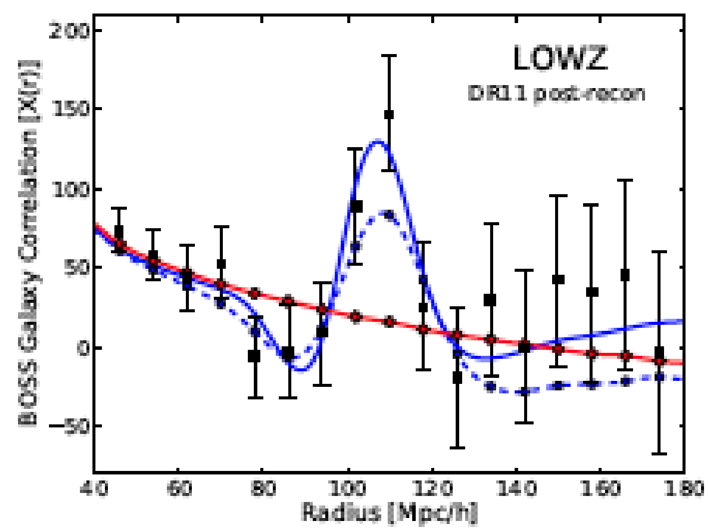
BAO in the 4yr BOSS Galaxy Sample

Anderson, et al., 2014

- Distance measured in two galaxy samples
- 2% precision at z=0.32
- 1% precision at z=0.57



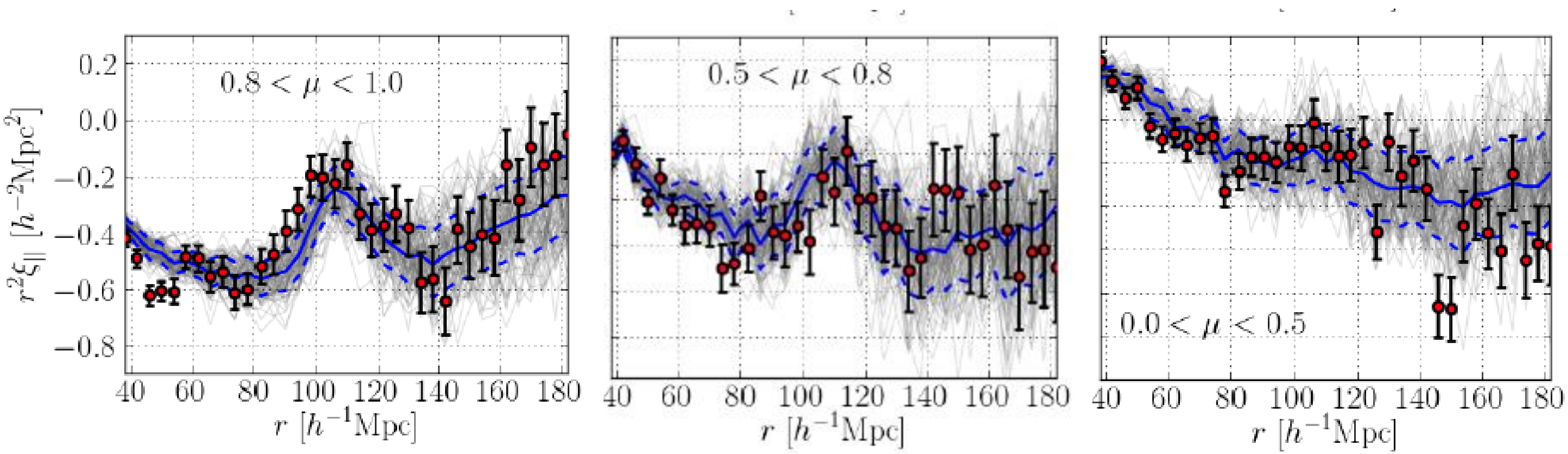




BAO in the 4yr BOSS Ly-alpha Forest Sample

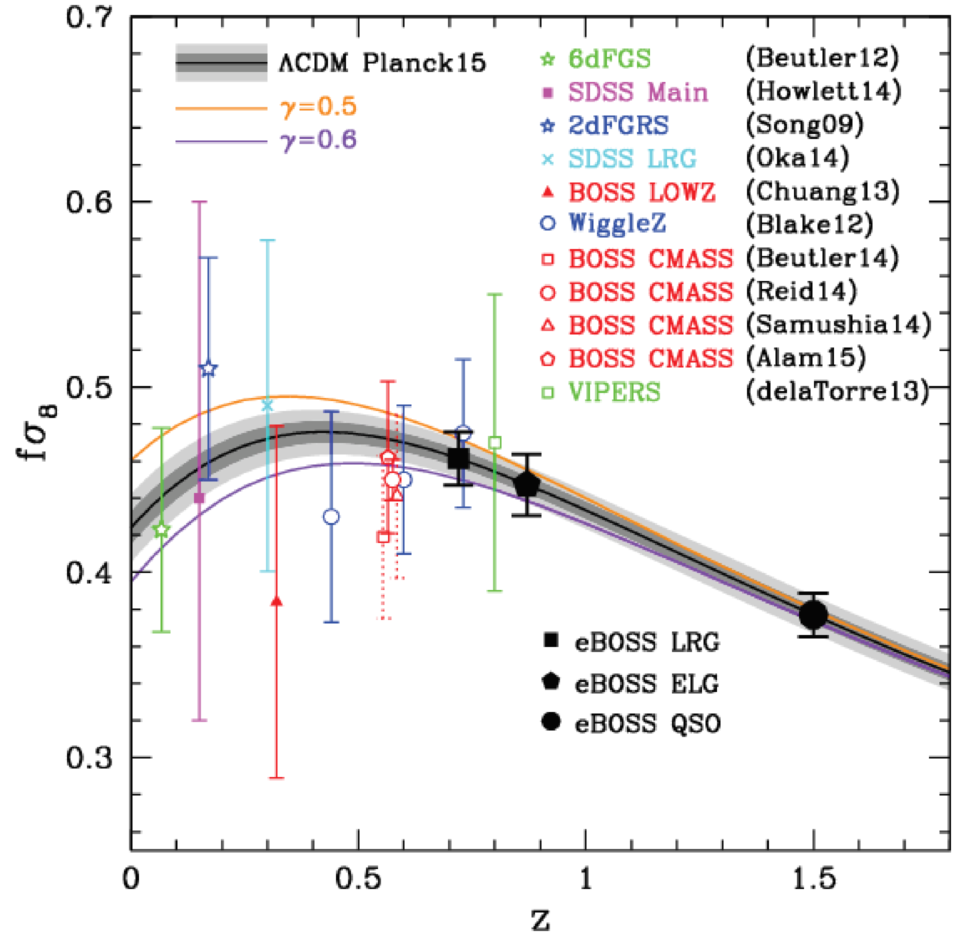
Delubac, et al., 2015

- Distance measured in d_A and $H(z)$
- d_A = 1662+/- 96 Mpc at z=2.34
- $H(z)$ = 222+/- 7 km/s/Mpc at z=2.34

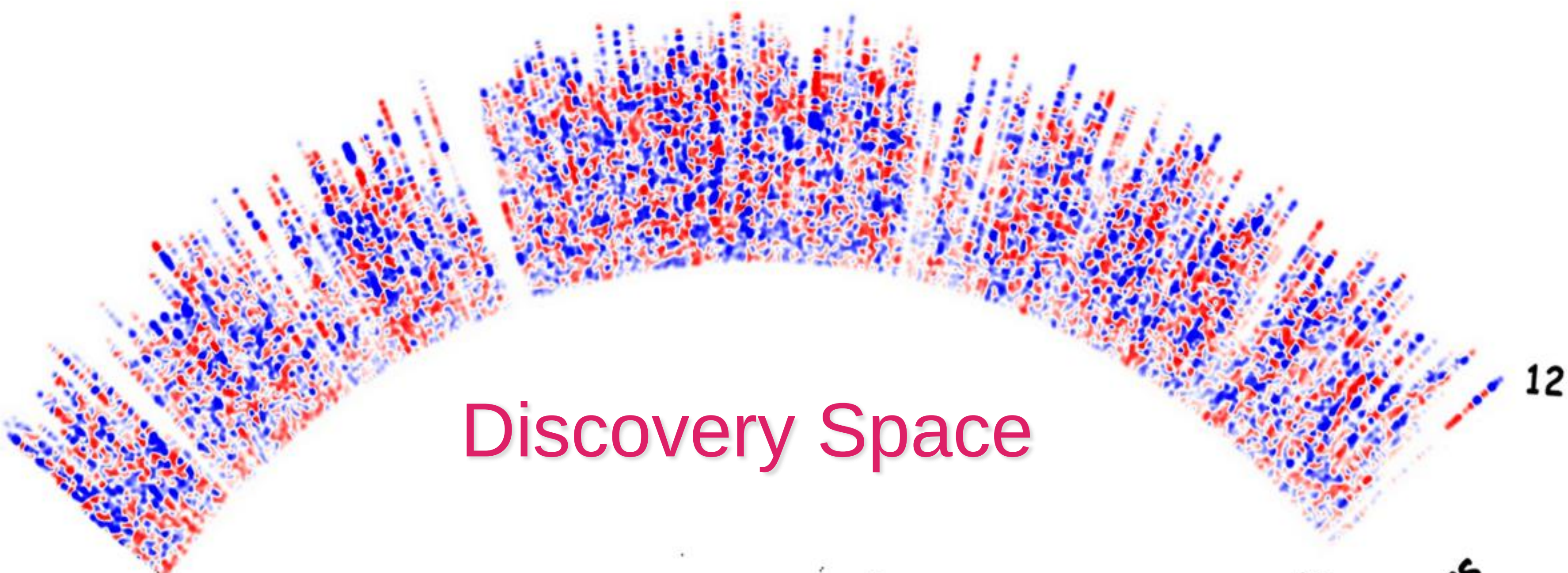


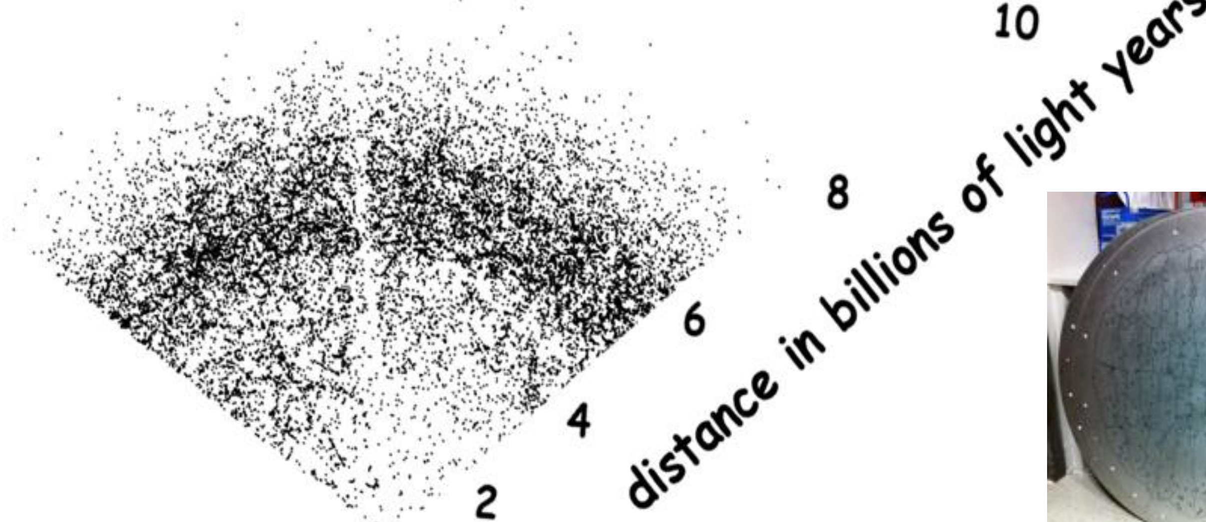
RSD in the 4yr BOSS Galaxy Sample

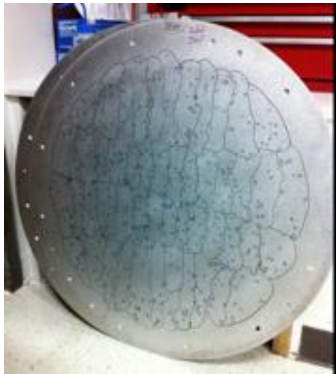
- Sensitive to f σ_8
- Growth rate and amplitude of matter fluctuations
- Wide redshift range required to decouple growth from amplitude
- Test of general relativity (GR) on cosmological scales



The Extended Baryon Oscillation Spectroscopic Survey







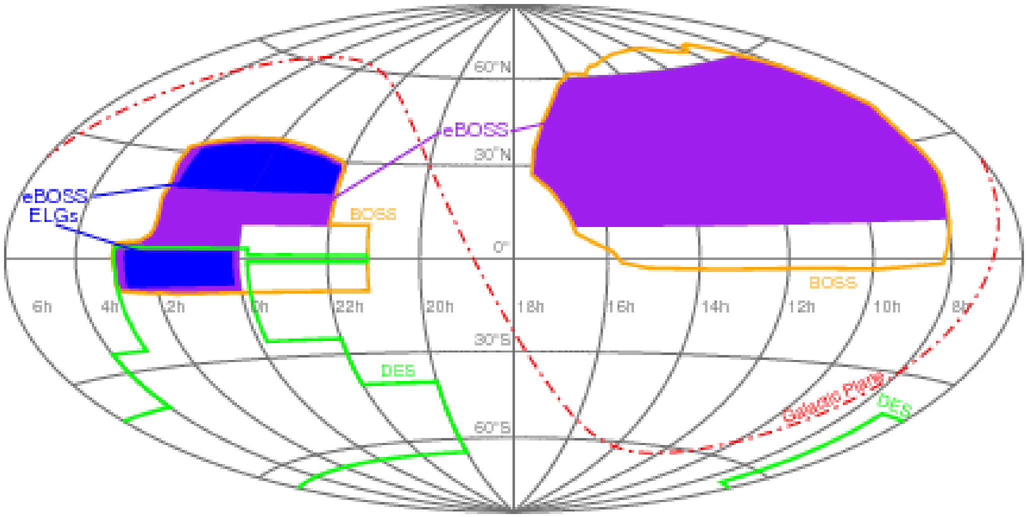
Extended Baryon Oscillation Spectroscopic Survey

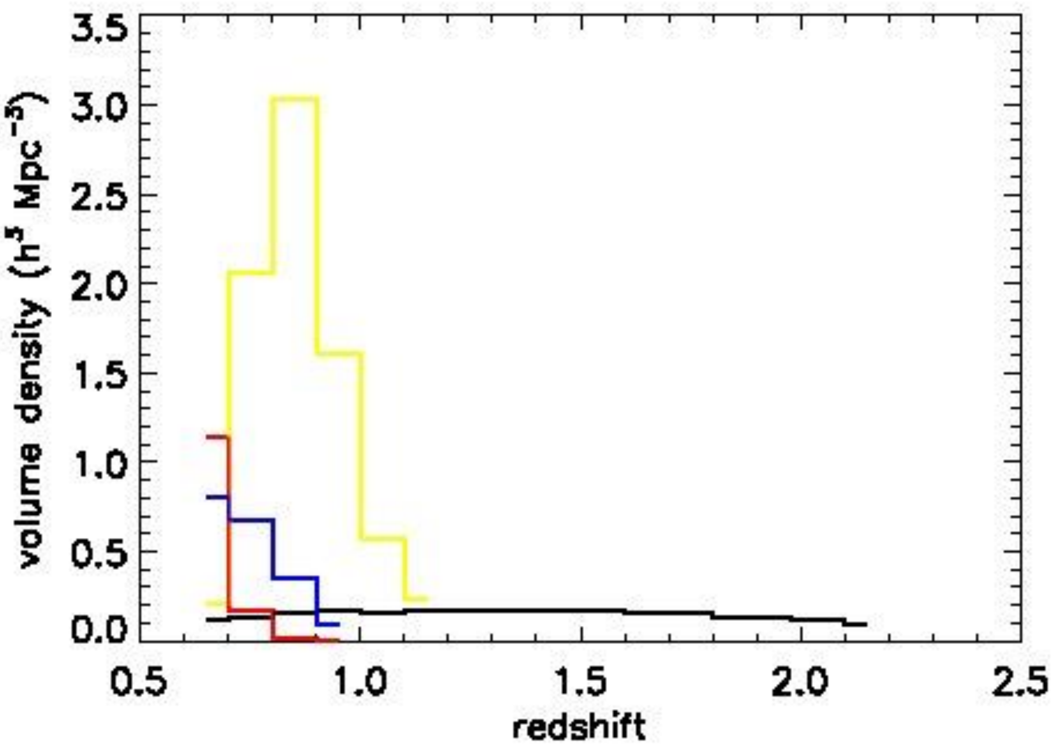
Dawson, et al., 2015

- Entirely new target selections since BOSS
  - Enabled by new imaging since 2009
- Luminous Red Galaxies (LRG; $0.6<z<1.0$; Prakash et al. 2015)
  - Selected from SDSS and WISE infrared satellite images
  - Higher redshift than BOSS galaxies, established methodology
- Emission Line Galaxies (ELG; $0.7<z<1.1$; Comparat et al. 2015)
  - Likely DECam selection
  - Test plates in November, decide final selection by Feb 2016
- Quasars ($0.9<z<2.2$; Myers et al. 2015)
  - SDSS/WISE with proven sample
  - Will allow first BAO measurement directly from quasars
- Lyman alpha forest ($z>2.1$)
  - Enhance BOSS program with 60k new and 60k reobserved QSO
  - Improve analysis algorithms and spectral data reductions

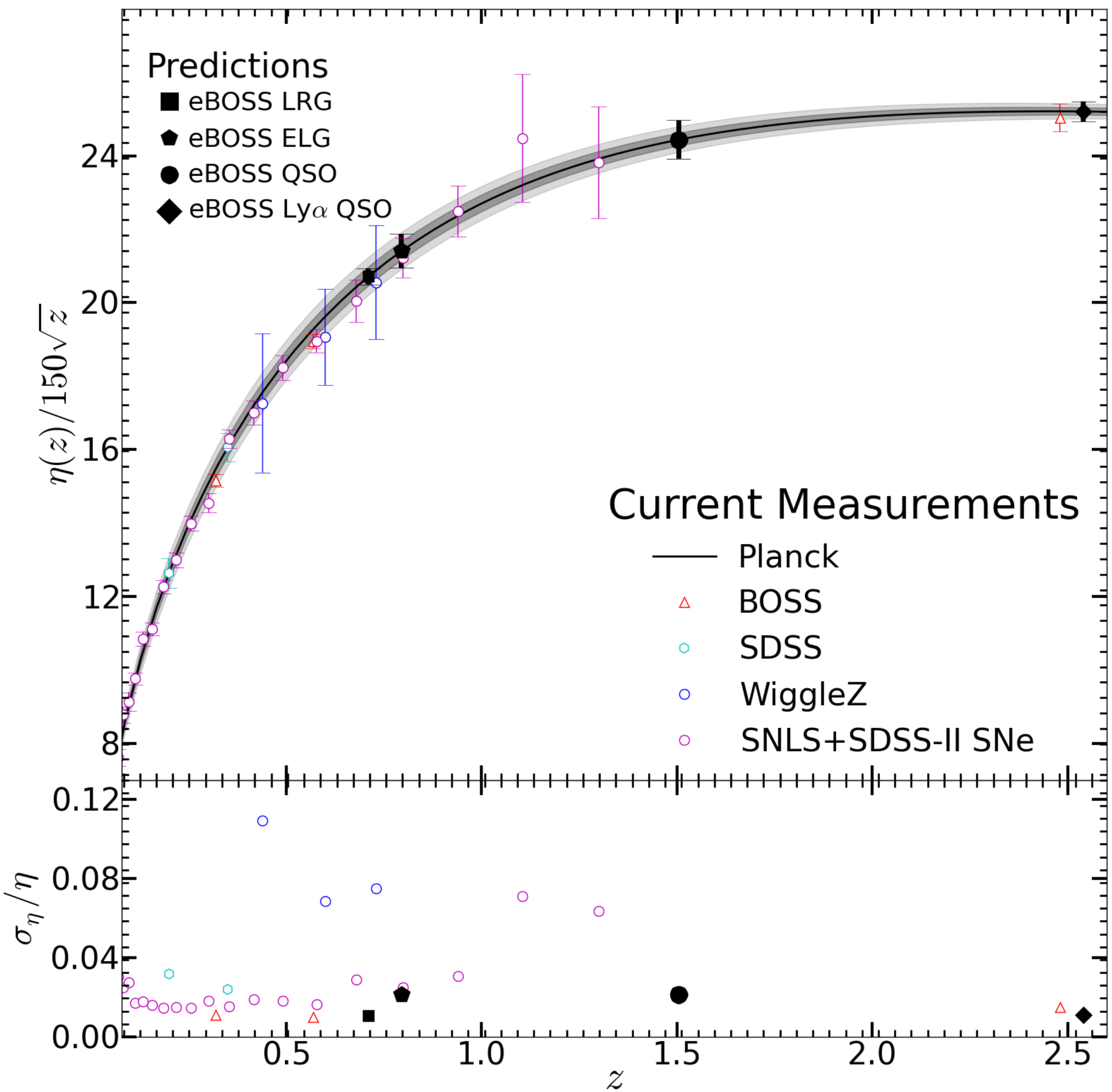
Survey Overview

- BOSS+eBOSS Tracers (z>0.6)
  - 175,000 BOSS galaxies (red)
  - 265,000 new LRG (blue)
  - 195,000 new ELG (yellow)
  - 500,000 QSO tracers (black)
  - >200,000 ly-alpha QSO
- QSO+LRG (all filled regions): 7500 sq degrees total
- ELG (blue): 300 plates up to 1500 sq degrees
- ~300 plates completed as of today





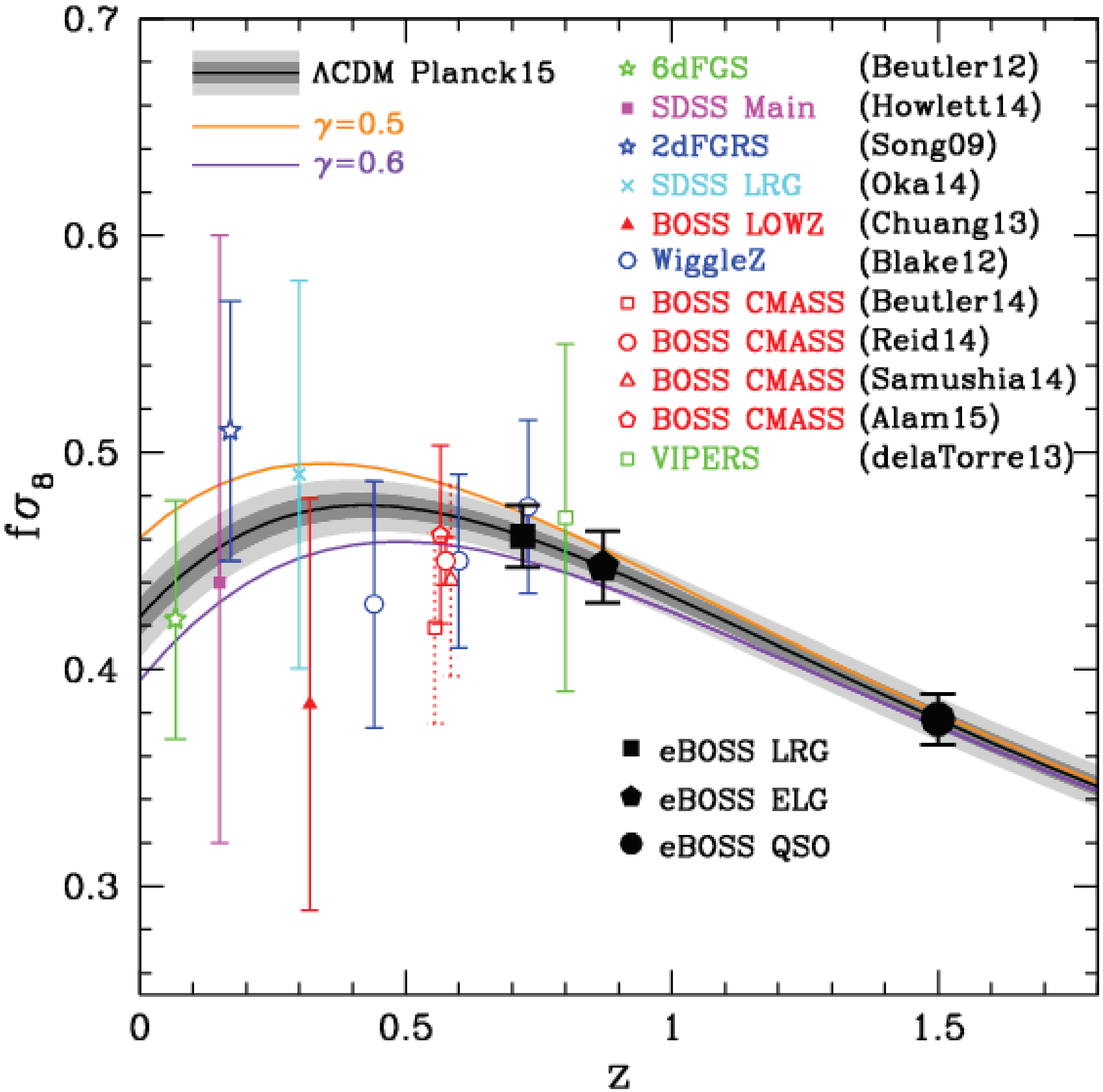
Predicted BAO Constraints



- Distance precisions 1-2% on all tracers
- LRG: 0.8%
- ELG: 2%
- QSO: 1.8%
- Lyman-alpha
  - 1.4% on H(z)
  - 1.7% on D_A(z)

Predicted RSD Constraints

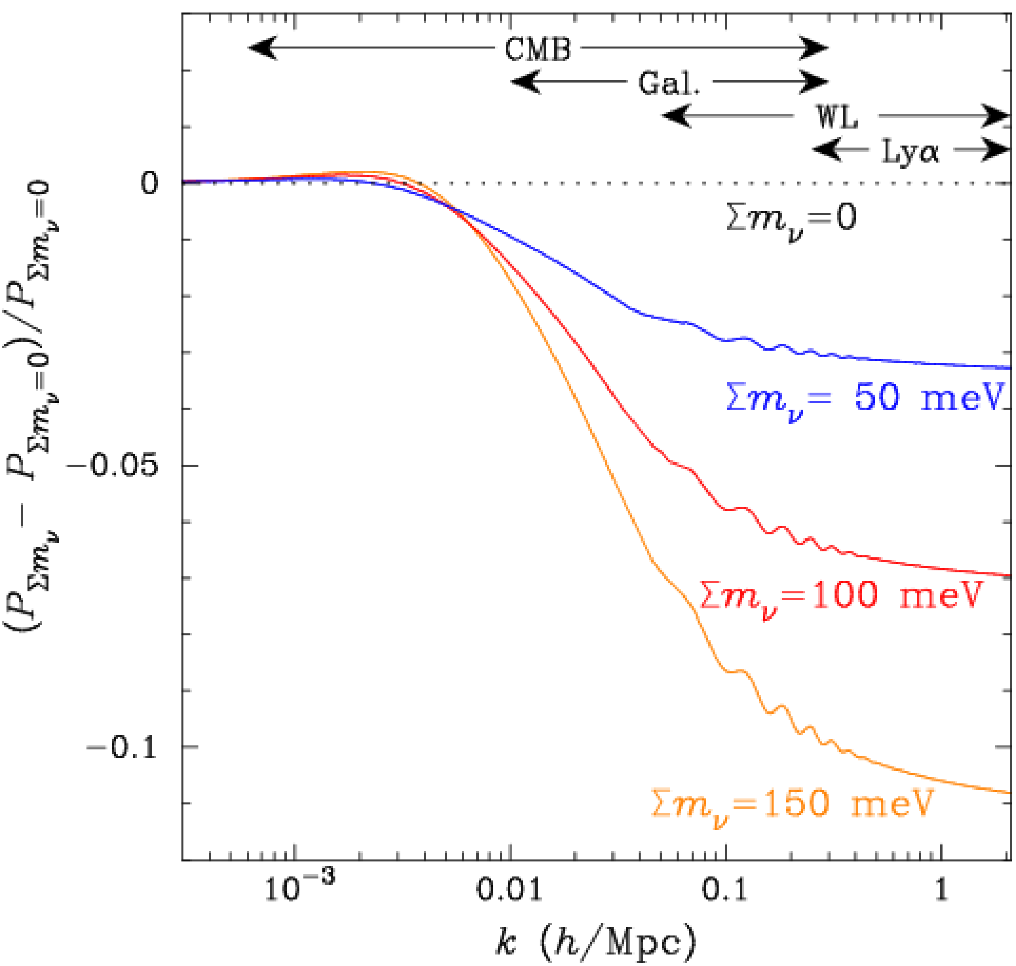
$$P_g^s(k,\mu_k) = \left(b + f\mu_k^2\right)^2 P_m^r(k)$$



- f σ_8 statistical precisions on galaxy and QSO
- LRG: 2.6%
- ELG: 3.8%
- QSO: 3.2%

- Challenge: Theoretical modeling

Predicted Neutrino and Inflation Constraints



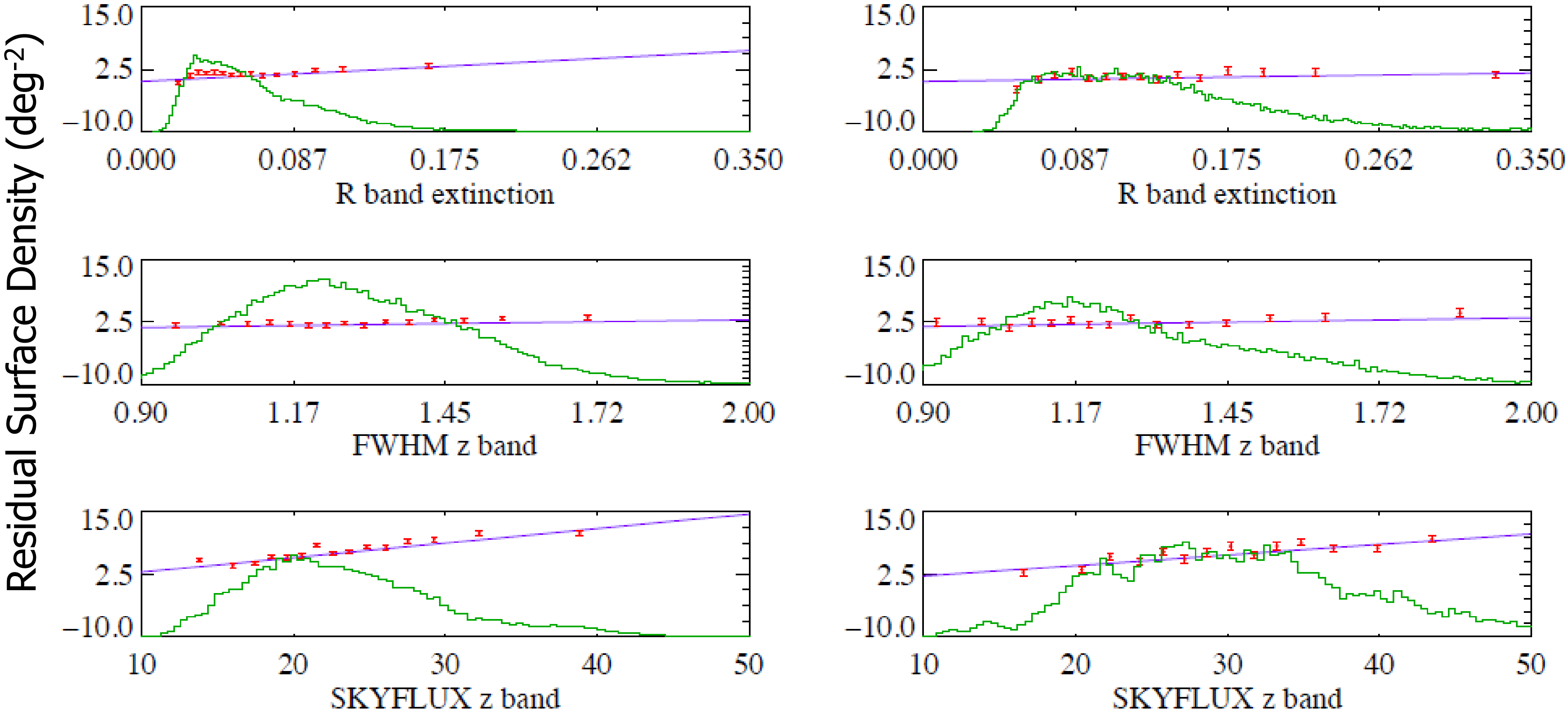
- Statistical precision from all tracers
  - Planck +spectro
  - Assume flat LCDM
  - $\sigma(m_\nu)$=36 meV k<0.2
  - Methodology introduced in BOSS, e.g. Beutler et al., 2014
- Inflation from Planck + eBOSS clustering
  - $\sigma(f_{nl})^{local}$=12 (power spectrum)
  - BOSS methodology, e.g. Ross et al., 2014
- Potential for improvement on f_{nl} with bispectrum
  - First tests in BOSS, e.g. Gil et al., 2014
- Challenge: Theoretical modeling

Challenges

- Fiber fed positioner depends on imaging for target selection
  - Convolves selection function across multiple surveys
  - Sensitive to calibration
- Galaxies at higher redshifts are faint and hard to classify
  - LRG ID-ed by absorption, need high S/N
  - ELG ID-ed by narrow emission, separate from sky residuals
- Detector technology well-developed but hard to increase by orders
  - Spectrographs are big
  - Fibers collide

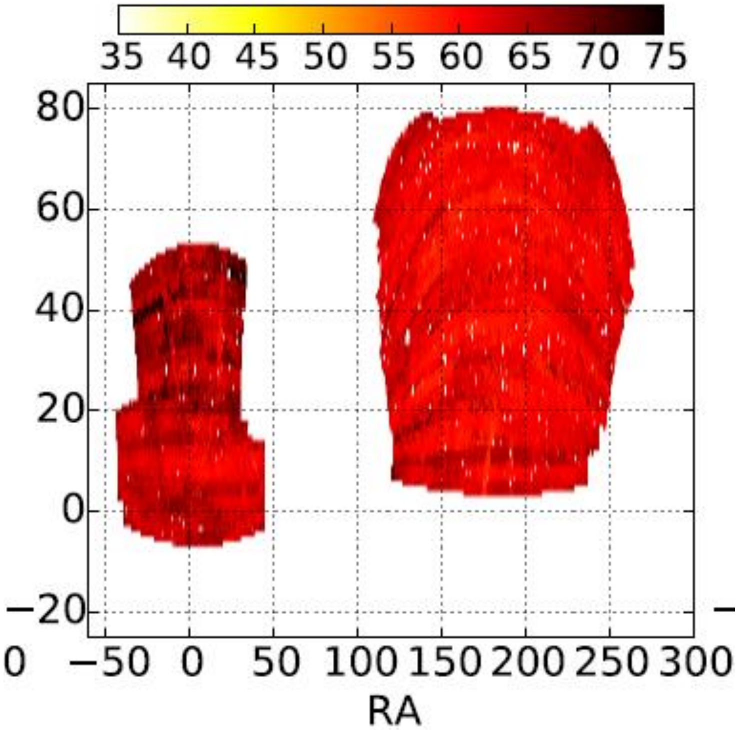
Target Selection Systematics

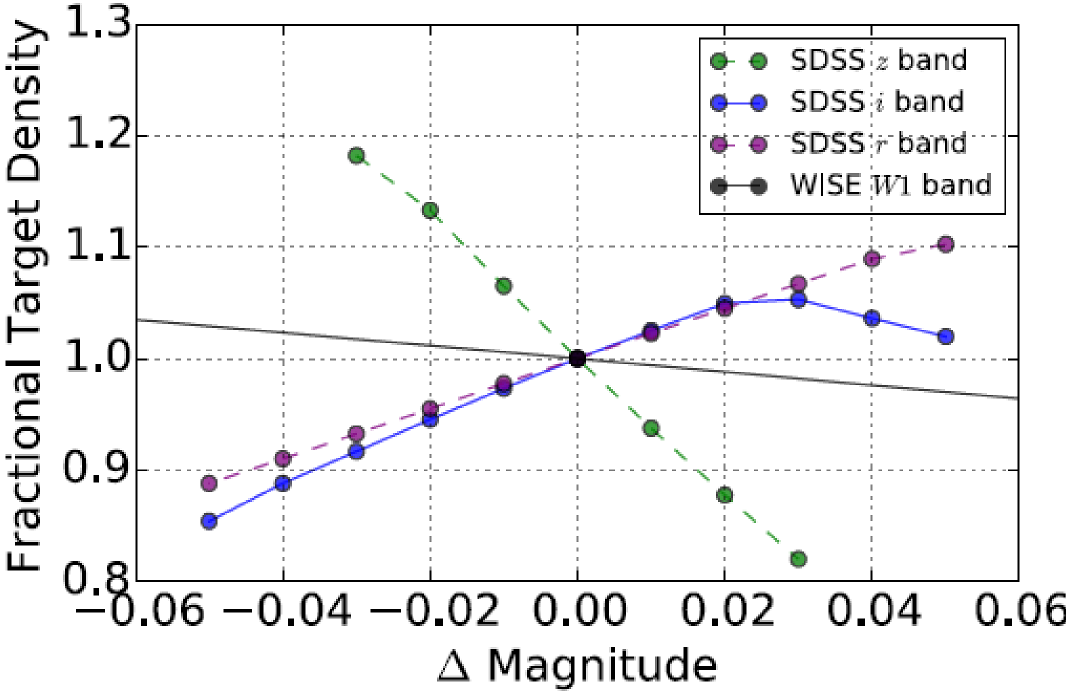
- Variations in imaging conditions introduce structure into target selection
- Steepest relationship on zband imaging conditions for LRG
  - 8% of area varies by >15% due to variations in imaging conditions
- Steepest relationship on image depth for QSO selection
  - 10% of area varies by >15% due to variations in depth



Target Selection Systematics

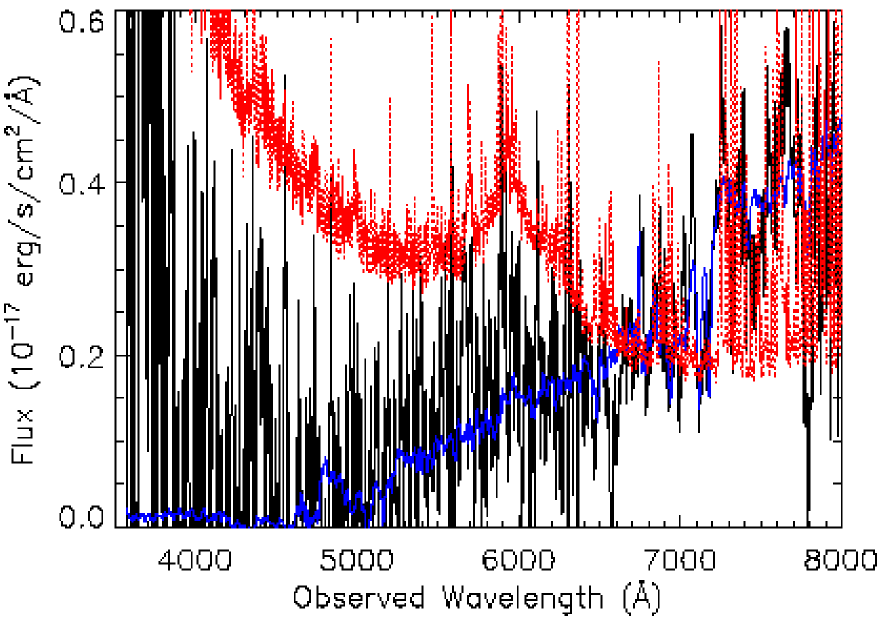
- Variations in imaging conditions introduce structure into target selection
  - SGC and NGC feature different systematics
- Calibration of imaging data essential
  - 0.01 magnitude rms errors in zband zeropoint cause 6.2% density change

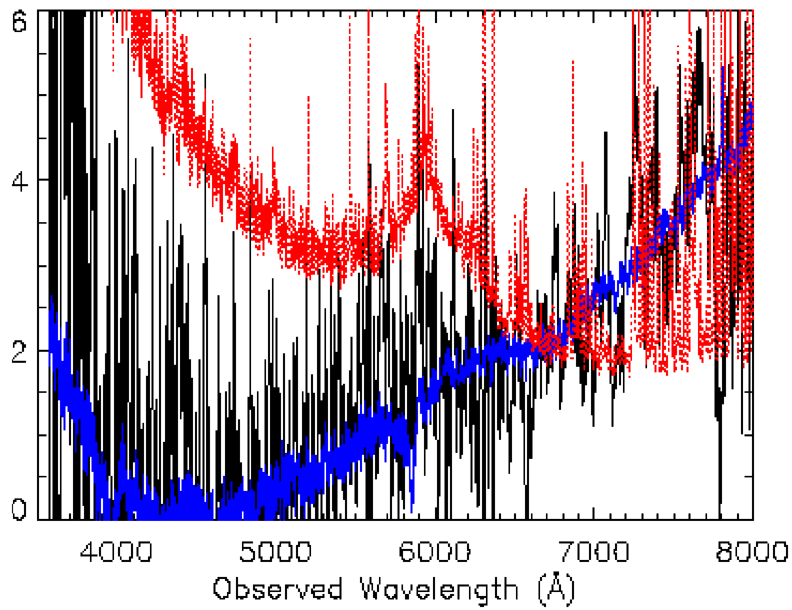




Spectroscopic Completeness

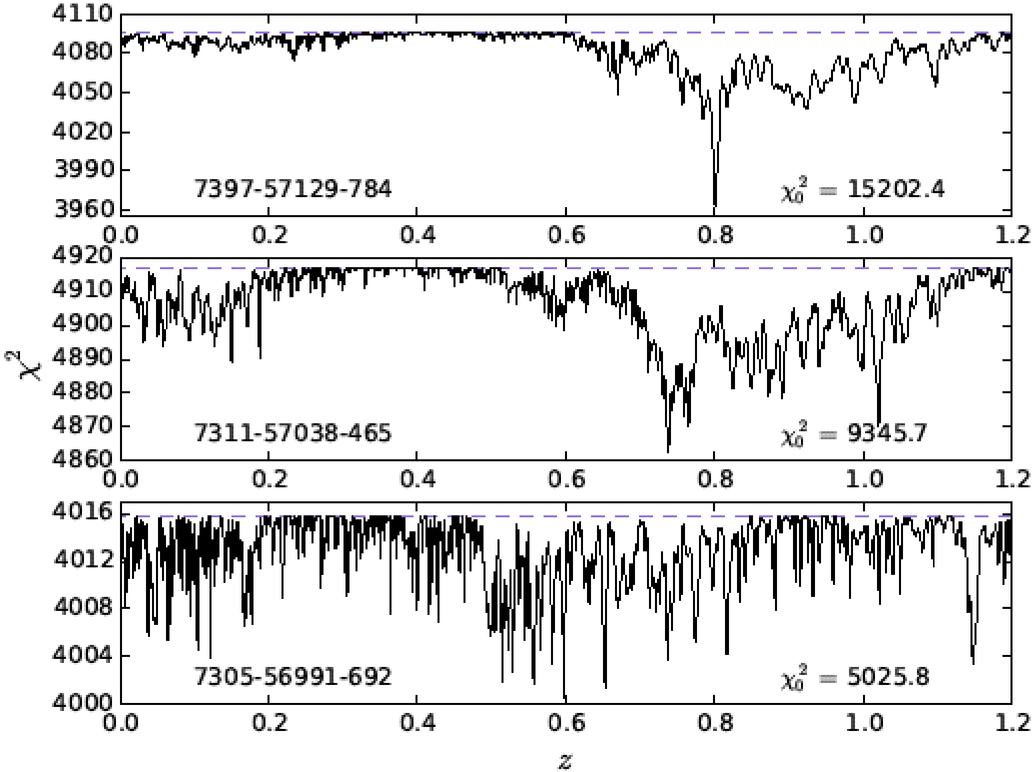
- Won't mention ELG spectra for now
- QSO → understand astrophysics to reduce systematics in redshift estimates
- LRG spectra are faint
  - Reduces classification efficiency relative to BOSS (30% failure if routines unchanged)
- Flux calibration is essential
  - Loss of information due to non-physical broad-band spectral features
  - Should improve with bench mount system

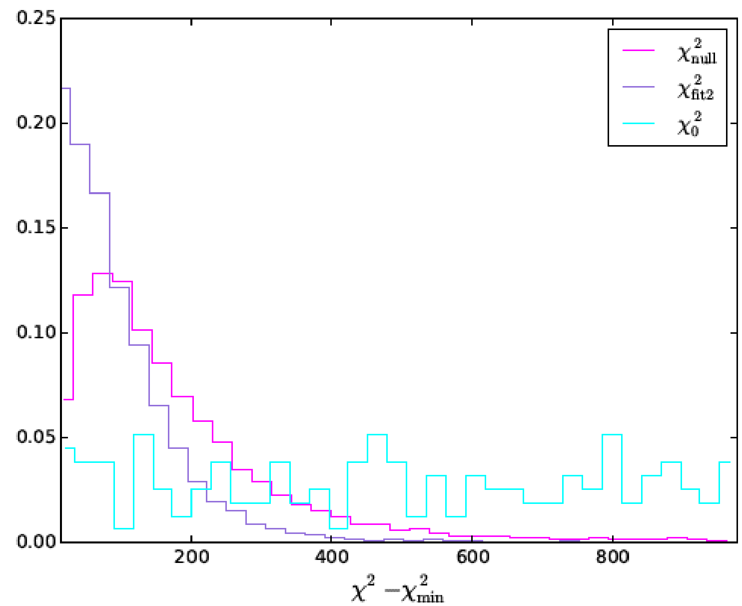




Spectroscopic Completeness

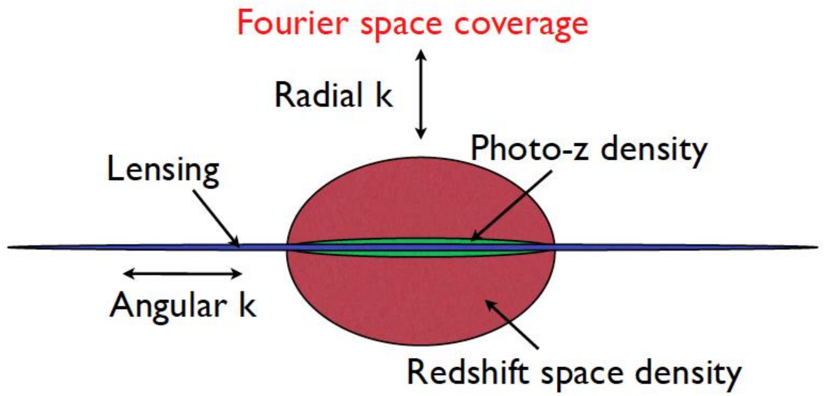
- LRG spectra are faint
  - Difficult to discriminate non-physical continuum from astrophysical signal
  - Sometimes low S/N as well





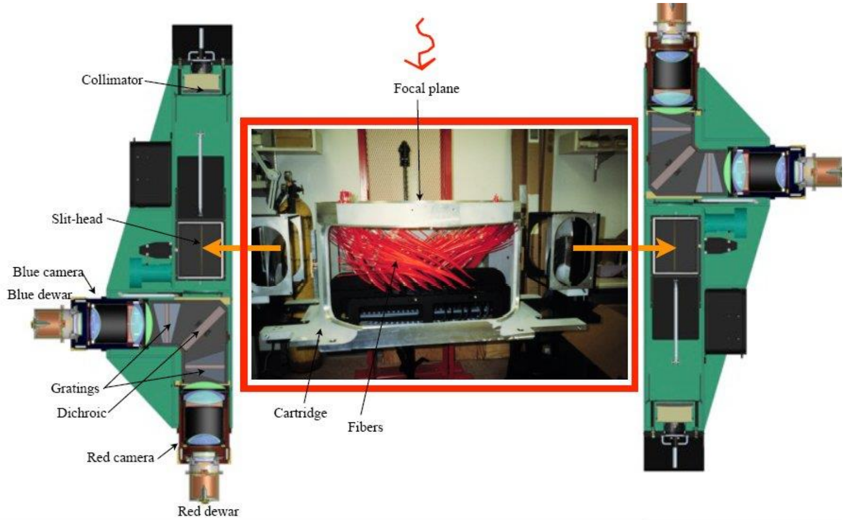
Statistical Limitations

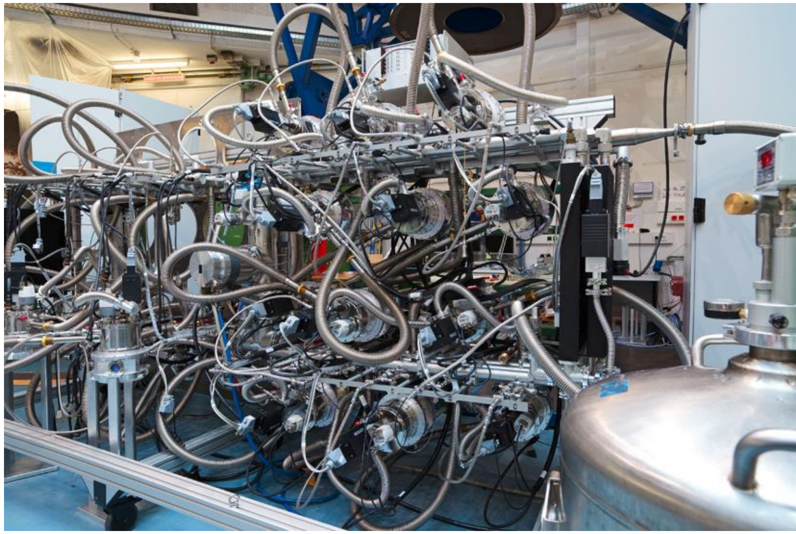
- BOSS/eBOSS 3 orders magnitude smaller sample than LSST
  - Galaxy population not well-sampled
- DESI - science reach still not statistically limited
  - Lack mixed bias tracers and modelling at small scales
  - Room to improve reconstruction of velocity field
- Statistics
  - More modes to explore
  - Mixed bias tracers → 3pt correlation for inflation
  - Mixed bias tracers → highly constrained models down to non-linear scales
- Degeneracy between modified gravity and neutrinos
  - 3X degradation in neutrino masses with Linder gamma parameterization
  - Worse degradation if invoking scale-dependent models of gravity



Spectrograph Challenges

- BOSS/eBOSS Spectrograph mounted to telescope
  - 1000 fibers at Cass
  - ~1.5M spectra
- DESI
  - 5000-fibers at prime
  - Benchmount of 10 spectrographs, each comparable to human height
  - ~35M spectra
- Bigger spectrograph on bigger telescope: large!
  - E.g. MUSE on VLT, 50 m^3 for 100,000 traces
  - MUSE at Nasmyth focus, image slicer
  - 8-m telescope
- Difficult to scale to orders of magnitude bigger than DESI
  - How to scale to 100'sM spectra?





Summary

- BOSS done
  - sets stage for BAO/RSD
- eBOSS
  - One year into survey
  - New tracers
  - Understanding selection function
- DESI
  - See next talk
- Future
  - How to scale to larger spectrographs?